



Sun-Earth Connection



The Plasma Universe

Comparative Environments

Mars

Earth

Venus

Mercury

Magnetospheres

Humans in Space

Satellite Operations

Power and Communications

Climate Change

Tracing the flow of energy and matter from the Sun and determining its effects on the solar system and on society.

Technology Roadmap

4/1/97

SEC Technology Overview

- **To accomplish the needed measurements, SEC missions will require:**
 - Miniaturized instruments
 - Access to light weight, low cost, & durable spacecraft systems
- **Exciting opportunities for high payoff technology to enable or significantly enhance SEC missions**
 - Constellations of advanced technology spacecraft
 - Advanced electronics, data, and communication systems
- **Many SEC technology requirements enhance other NASA missions.**
 - Light weight, multifunctional spacecraft components
 - Advanced propulsion and power technologies

Technology Roadmap Overview

- **Identification of technology needs is driven by SEC science requirements**
- **The SEC Technology Working Group was established to develop a technology roadmap. This was accomplished at a workshop with participants who are NASA, university, and industry scientists and engineers**
- **Technology requirements centered around three general areas:**
 - **Sensors & Instruments**
 - **Spacecraft Systems**
 - **Transportation & Mobility**
- **Finalized roadmap (to include schedule & performance metrics) will be developed after SEC mission priority sequence is determined**

Sensors and Instruments: Introduction

- **Sensors and instruments are the primary means by which scientific measurements are made. Technology development is necessary to enable measurements that will advance the knowledge and understanding of Sun Earth Connections.**
- **Because of the diversity and multiplicity of the physical parameters that characterize the space environment, many types of sensors and instruments are needed. However, the technologies are linked by five common elements:**
 - Innovative Measurement Techniques**
 - Sensing Elements**
 - Focal Plane Detectors**
 - Front-end Electronics**
 - System Miniaturization**

Innovative Measurement Techniques

What is needed

- New techniques to observe physical parameters that cannot now be measured in the space environment

Goal and Benefit

- Fill critical measurement gaps that limit our understanding of physical phenomena
- Measure with greater certainty key parameters that now can be inferred only indirectly
- Open new frontiers of space physics exploration

Today's State-of-the-Art

- Techniques do not exist or cannot be used for space flight applications (e.g. dust spectrometry)
- Some parameters can be inferred only indirectly (e.g. electrical current density)
- Some parameters can be measured only with inadequate sensitivity or resolution (e.g. very low energy neutral atoms)

Suggested Examples

- Very Low Energy (Sub-keV) Neutral Atom Imaging (H, D, He, Li, CNO)
- Electrical current density measurements
- Dust mass/charge spectrometry

Sensing Elements

What is needed

- Miniaturized and/or optimized designs for the collector component of space instruments (e.g. photon or particle optics, antennas, probes)

Goal and Benefit

- Achieving state-of-the-art performance with greatly reduced spacecraft resource allocation
- This would enable compact, lightweight instruments that could be deployed on small spacecraft

Today's State-of-the-Art

- Current technologies consume spacecraft resources an order of magnitude larger than will be available for many of the candidate missions

Suggested Image

- Miniature MEMS magnetometer probe (APL)
- Light weight mirrors
- Two - dimensional charged - particle optics systems
- Optimized x-ray optics (eg. multi-layers, glass capillary lenses, coded apertures)

Focal Plane Detectors

| What is needed | Goal and Benefit |
|---|---|
| <ul style="list-style-type: none">• Faster and higher resolution analysis of critical phenomena• Enhanced sensitivity and space/time resolution of energetic particle distributions | <ul style="list-style-type: none">• Comprehensive capability of measuring the mass, energy and angular distribution of charged particles. This will reduce the number of sensors that are required.• Increased spectral resolution and sensitivity, which will result in compact detectors with improved performance |
| Today's State-of-the-Art | Examples |
| <ul style="list-style-type: none">• One-dimensional spectrographs with only a few pixels• Pixellated detectors• Heavy, bulky energetic particle detectors (>10 kg)• Two - dimensional imaging x-ray proportional counters | <ul style="list-style-type: none">• Multi-pixel Monolithic Energy/Mass Spectrograph• Delta Doped CCD (low energy)• Integrated CCD/Active Pixel Sensors• Compact, lightweight energetic particle detectors (< 1 kg)• Solid - State X-ray Imaging Spectrometer |

Front End Electronics

What is needed

- Faster and higher resolution analysis of critical phenomena
- Enhanced sensitivity
- High density analog/digital hybrid circuit design
- Standardized digital output interface

Goal and Benefit

- Multichannel asynchronous pulse analysis circuitry
- High throughput event analysis (>MHz)
- Parallel - processing of multi-pixel array outputs
- Reduced resource requirements

Today's State-of-the-Art

- Discrete amplifiers and pulse conditioning circuits
- High power/volume consumption for high speed analyzer channels
- Excessive time required to acquire complete images

Suggested Examples

- Multipixel asynchronous pulse-height analyzers
- Multichannel (100-1000) time-of flight coincidence logic and time digitization circuitry
- Integrated functions into much smaller power/volume envelope

System Miniaturization

What is needed

- Overall reduction in spacecraft resource requirements that result in smaller, lower - cost spacecraft
- Instrument mass, volume, and power requirements must be reduced to be compatible with deployment on microspacecraft

Goal and Benefit

- Compact, light weight sensors can enable microspacecraft constellations that can be deployed with smaller launch vehicles at affordable cost
- Compact, light weight sensors on microspacecraft that result in shorter travel time to the outer planets and interstellar medium

Today's State-of-the-Art

- Instruments generally have a mass of tens of kilograms and power consumption of tens of watts
- Instrument electronics generally consist of multiple analog and digital circuit boards

Suggested Examples

- Miniaturized Mass Spectrometer (<1 kg)
- Electronics Packaging (e.g. chip-on-board, multi-chip module)
- Very Large Scale Integrated Circuits (VLSI)
- Low-mass, low-power cryocoolers
- Light weight, multifrequency plasma wave sensors

Sensors and Instruments: Summary

- **Improvements in sensor performance and reductions in instrument resource requirements will directly enable the utilization of compact, light weight spacecraft.**
- **Technology advances in each of the five critical elements are required. This can be accomplished by a competitively selected, peer-reviewed program for SEC Instrument Design and Development Program (Similar to the existing Planetary Instrument Design and Development Program) that is targeted for the SEC Roadmap science missions.**

Spacecraft Systems: Introduction

- **SEC spacecraft technology needs in general share four common attributes**
 - Affordability
 - Survivability
 - Lightweight
 - Long-lived

- **Spacecraft technologies grouped in nine areas:**
 - Architectures & Interfaces
 - Operability & Communications
 - End-to-End Devel. Environments
 - Structure, Materials, & Mechanisms
 - Radiation Hardened/Tolerant Space Data Systems
 - Advanced Packaging
 - Power Systems
 - GN&C
 - Software (Flight & Ground)

Needed Characteristics of Sun-Earth Connection Spacecraft

- More **affordable** spacecraft without loss of capability
 - Enables constellation type missions
 - Allows greater fraction of resources for direct science content
- Compact and **lightweight** spacecraft
 - Lower mission launch costs
 - to allow use of low cost launch vehicles
 - allow more spacecraft in a given vehicle
- **Long-lived** spacecraft at low cost
 - Enables many year or long transit time missions
- Spacecraft which can **survive** and operate in extreme radiation and thermal environments without costly, unique design modifications
 - Enables types of missions which are now too costly

Affordability - Constellations

What is needed

- Lower component costs through the use of standard and configurable components
- Lower I&T costs through use of standards and configurable components and automated assembly and testing
- Innovative architectures to coalesce functions
- Software standards/re-use to allow low cost functional extension and adaptability
- Lightweight S/C to minimize launch costs

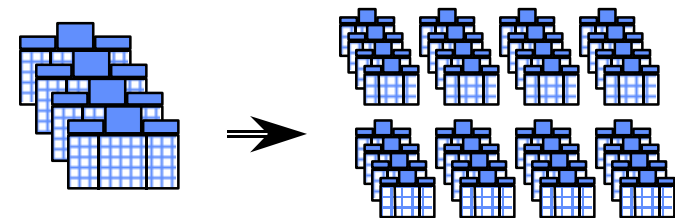
Goal and Benefit

- Lower overall mission costs
- Allow acquisition of large number constellations of satellites
- minimize time and cost of assembly and test
- improve reliability through re-use of thoroughly tested components

Today's State-of-the-Art

- single purpose, non-configurable, stock components
- data bus standards
- no power, software or information standards
- reliability heavily dependent on workmanship and testing

Today's State-of-the-Art and Goal



**4 Spacecraft
Grand Tour Cluster
MIDEX Proposal**

**Many Spacecraft
Constellations for
the same cost**

Lightweight Spacecraft

What is needed

- Low cost lightweight structures
- Dense packed avionics
- lightweight combined function components
- Integrated structure and avionics
- advanced power & data bus architectures
- Low cost robust actuators

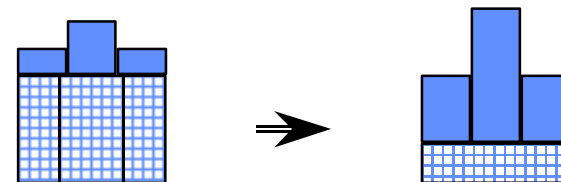
Goal and Benefit

- Enable Multiple In-Situ Measurements of Geospace Environment
- Lowers mission cost by allowing the use of less expensive launch vehicles
- Shortens transit times
- Lowers propulsion requirements and cost
- Enable use of sails
- Allows greater mass fractions for instrumentation

Today's State-of-the-Art

- built-up composite structures
- cast aluminum structures
- surface mount electronics
- 1773 data bus
- solid state power switch with ESN

Today's State-of-the-Art and Goal



**30-70%
spacecraft
mass fractions**

**10-20%
spacecraft
mass fractions**

Long-lived Spacecraft

What is Needed

- Radiation immune systems
- Non-degrading mechanisms
- Non-degrading energy storage
- Understanding hostile space environments
- Accurate spacecraft design criteria
- Development of environmental mitigation techniques

Goal and Benefit

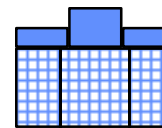
- Allow build-up of pay-as-you-go constellations
- Enable long-term missions without multiple launches
- Facilitate design, manufacture, and operation of cost-effective spacecraft
- Achievement of mission objectives within cost and schedule constraints

Today's State-of-the-Art

- 3+ year single string buses
- Radiation shielded 5 Krad-electronics
- Sensitive mechanisms
- Degrading solar arrays
- Degrading batteries
- Limited environmental models (primarily LEO)
- High margins in environmental designs leading to conservative designs with increased cost

Today's State-of-the-Art and Goal

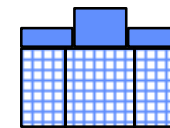
3 Years



**Low cost,
single string
bus with 3 year
predicted life**



15 Years



**Low cost,
single string
bus with 15 year
predicted life**

Survivability

What is Needed

- Systems that can operate in the near-sun environment with minimum constraints
- Systems that can operate in high radiation environments without degradation, constraints, or high overhead
- Systems that can utilize meteoroid mitigation or repair techniques for continued operation
- Understanding the nature of hostile space environments
- Accurate spacecraft design criteria
- Development of environmental mitigation techniques
- Development of the understanding of environmental effects on new technologies (materials, electronics, etc.)

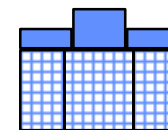
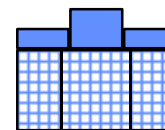
Goal and Benefit

- Allow flexible, low-cost near-solar missions
- Allow flexible, low-cost high-radiation environment missions
- Accurate environmental design margins leading to lower cost spacecraft

Today's State-of-the-Art

- Limited environmental models (primarily LEO)
- High margins in environmental designs leading to conservative designs with increased cost

Today's State-of-the-Art and Goal



**Low cost bus
bus room temp
avionics, 5 Krad
tolerance; degrading
performance**

**Low cost bus
with high
temperature and
radiation tolerance;
self compensating
performance**

Architectures and Interfaces

What is Needed

- Non-Proprietary, Flight H/W & S/W Interfaces Based Upon Commercial Standards to Enable a “Plug & Play” flight architecture
- Flexible Architectures That Encourages Both Revolutionary & Evolutionary Improvements, Design Reuse, and COTS GSE and Development Tools
- Adaptable Systems for Fault Tolerant and Single String Architectures

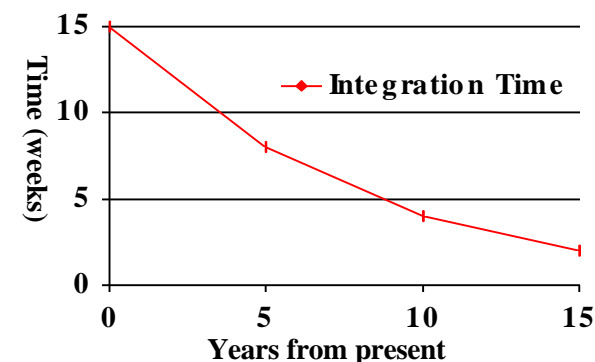
Goal & Benefit

- Long Lived, Low Cost Architecture Adaptable to Most Missions
 - Increased Design Reuse
 - Shortened Development Time
 - Easier Integration
- Support Technology Driven Improvements With Minimal (or no) Impact on Other Systems
 - Concentrate on Mission Unique Needs, Not the Bus

Today’s State-of-the-Art

- Heritage Systems That are Redesigned From Mission to Mission
- Proprietary Interfaces with Restricted Sources
- Attempts at using standards are limited
 - Heavy Modifications Affects Interoperability
 - Loses Most Benefits of Using a Standard

Total Observatory Integration Duration



Operability and Communications

What is needed

- Architectures Supporting Variable and Fixed Formation Nodes
- Two-way Communication System Supporting Multiple, Distributed Nodes
- Improved specific bandwidth
- Autonomy and automation to enable goal oriented commanding
- Autonomous formation flying

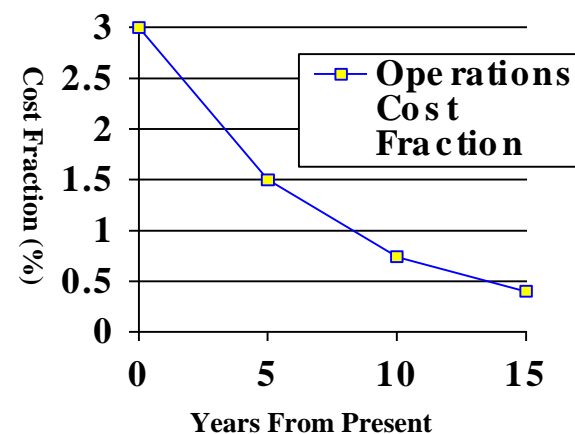
Goal and Benefit

- Operate science and communication constellations with 100's of nodes
- Minimize Comm System Impact on Satellite Power, Mass, Volume Requirements
- Minimize operations cost to enable long duration missions
- enable long distance, high rate communications

Today's State-of-the-Art

- Engineering and operator intensive operations
- single satellite to ground links
- Spacecraft and program resource intensive communications systems
- long range communications only with large, expensive space and ground assets

Operations Mission Cost Fraction per Year of Operations



Advanced Packaging

What is Needed

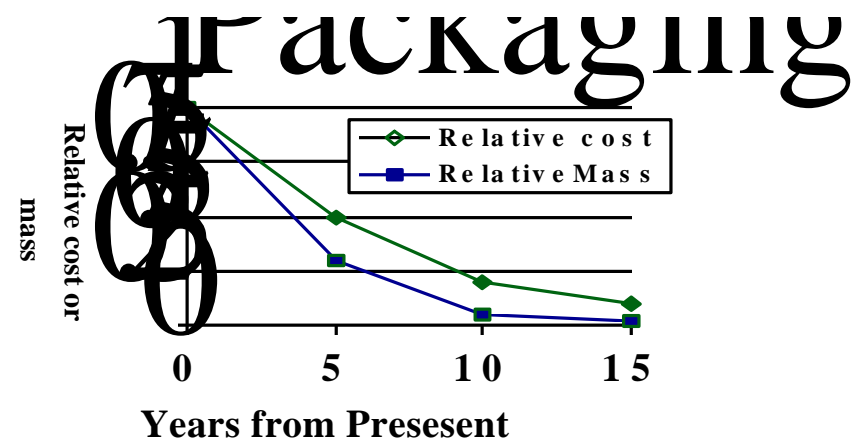
- Significant Reductions in Mass, Size, Power and Cost of Avionics Systems
- Rapid/Inexpensive Development of Prototype & Flight Miniaturized/Dense Avionics Systems
- Mixed Technology Support
 - Digital
 - Analog
 - RF
- Improved Interconnect Technology

Goal & Benefit

- Micro Spacecraft Avionics Systems Will be Achieved
 - Packaging Volume Improvements of 20X
 - Mass Improvements of 15X
 - Cost improvements of 5X
- Shorten Development Schedules by 2X

Today's State-of-the-Art

- Through Hole and Surface Mount Technology using Hermetic Packaging
- Minimal use of High Density Packages
- Minimal use of High Density Interconnects
 - Elastomeric Connectors
 - Fuzz Buttons



Power Systems

What is Needed

- Power Conversion
 - Lower Cost, High Efficiency Solar Arrays
 - Tether Systems
 - Advanced RTGs
- Energy Storage
 - Low Cost, Robust Batteries
 - Flywheel Energy Storage
 - Molten Salt
- Power Management & Distribution
 - High Efficiency Converters
 - Tailored Bus Voltages
 - High Density Packaging

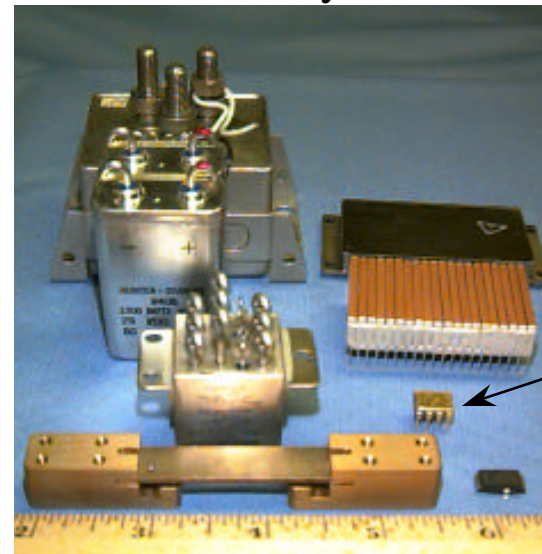
Goal & Benefit

- Low Cost, Reliable, Safe Power Systems for SEC Missions
 - Cost 1/3
- Long Life, Highly Efficient Power Conversion & Storage
- Battery Capability Increase of 3X
- Array Efficiency Increase of 2X

Today's State-of-the-Art

- GaAs/Ge Solar Cells (18.5% Efficient)
- 60W/Kg Solar Arrays
- NiH2 Batteries (32 W-hr/Kg)
- 28V, 90% INTER CONV. Systems
- 200W/Kg PMAD

Today's State-of-the-Art



**Volume
Reduction of
86%**

**Weight
Reduction of
78%**

Radiation Hardened/Tolerant Space Data Systems

What is Needed

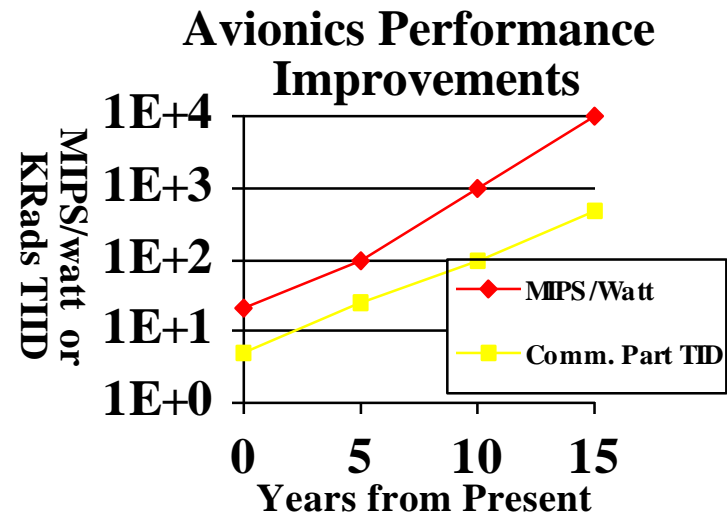
- Dramatic Increase in Performance (MIPs, MIPs/Watt)
- Significant Reductions in Mass, Size, Power and Cost
- Affordable Rad Hard/Tolerant VLSI based upon a Commercial Process
- Fault/Radiation Tolerant Architectures Based upon Commercial Technologies and Development Systems

Goal & Benefit

- Large-Scale On-Board Science Data Analysis to Mitigate Downlink Limitations and Reduce Mission Costs
- Enable Science Driven Autonomy
- Rad Tolerant ,Commercially Based VLSI at Costs Far Below Historic Levels
- 100-1000 MIPs/Watt scaleable to 10^5 MIPs by 2003
- Commercially Available VLSI @ 100K TID, No SEE (SEU or SEL)

Today's State-of-the-Art

- Power Efficiencies of 1-2 MIPs/Watt
- Total Performance of 20-40 MIPs (e.g..., Pathfinder, Mongoose)
- Radiation Hardening Requires 3 yr. - Costs 10X of Commercial Part
- Fault Tolerance by Block Redundancy
- Limited On-Board Autonomy



GN&C

What is needed

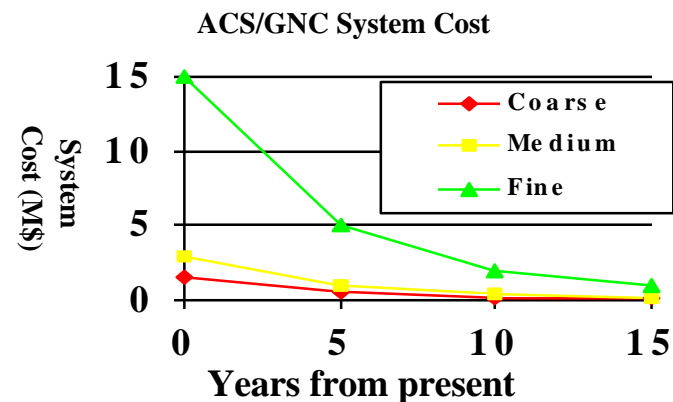
- Lower cost Guidance and Control systems in three ranges
 - Coarse package performance:
 - Attitude Control and Knowledge : better than 1 degree
 - Position better than 500 meters; veloc. better than 1 m/s
 - Medium package performance:
 - Attitude Control and Attitude Knowledge : 0.01 to 0.1 degree
 - Position better than 20 meters; veloc. better than 0.03 m/s
 - Fine package performance:
 - Attitude Control and Attitude Knowledge : 0.1 to 36 arcsecond
 - Position better than 5 meters ;veloc. better than 0.007 m/s
- Autonomous ACS/GN&C techniques to reduce mission systems and operations costs

Goals and Benefit

- Develop Low cost enabling and enhancing technologies in ACS sensors, actuators and attitude determination and control algorithms
- Develop Low cost enabling and enhancing technologies in navigation systems
- Develop information standards and techniques to allow the rapid and low cost analytical and physical integration and test of ACS/GNC systems
- The above will allow the acquisition of lower cost space systems in shorter times

Today's State-of-the-Art

- Fine package systems at \$15 M
- Design, Acquisition, integration and test sequence at 2-3 years total



End to End Development Environment

What is needed

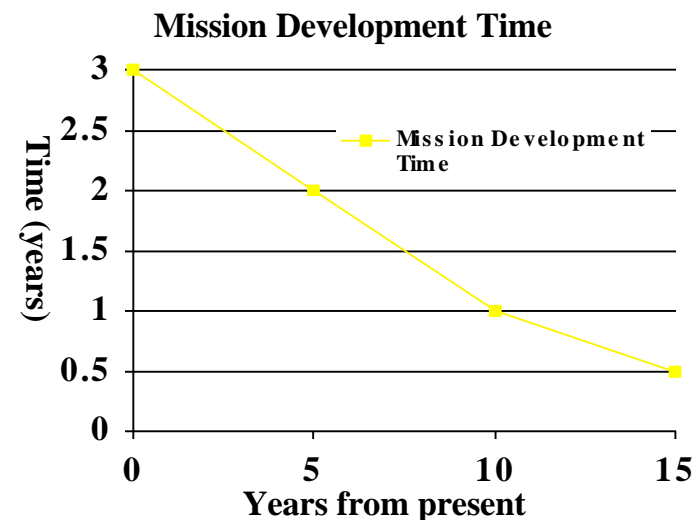
- Near real time simulation and visualization
- Common database design tools
- Interoperable design tools
- Art-to-part and rapid prototyping capability
- Seamless, Low cost virtual/physical hybrid testbeds

Goal & Benefit

- Optimize design for maximum science per unit cost
- Minimize design margins and excess requirements to lower costs
- Minimize analytical integration costs
- Minimize cost of translation errors
- Minimize cost by shortening development time

Today's State-of-the-Art

- Limited simulation capability
- Sequential design process
- Translation of design data between tools



Structures, Materials, & Mechanisms

What is Needed

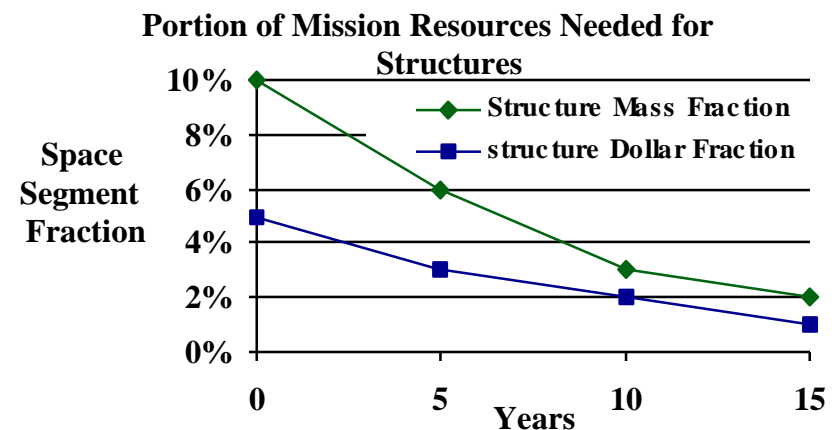
- Lwt, stable high-temperature-stable materials & structural components; low cost fabrication
- Films & coatings for debris, radiation, atomic gas environments
- Multifunctional structures. (loads, thermal, etc)
- Precision deployable antennas, instrument structures; inflatable spacecraft components
- Lightweight instr. structures, tunable mirrors
- Wide-temperature-range mechanical actuators, vibration. isolators; MEMS concepts
- Low cost, long-life, wide-temperature bearing, hinge, latch/unlatch devices

Goals and Benefits

- Reduce launch & transfer costs via light weight materials
- Affordable fabrication reduces cost, increases performance potential
- Enable long-life, extreme-env. survivability, via robust materials (e.g. solar sails, instr.)
- Compact packaging, reduced part-count via combined-function components, MEMS
- Reliable deployment, in-flight reconfiguration/operations
- Actively controlled structures enable robust, tunable designs
- Reduced power & internal heating

Today's State-of-the-Art

- Graphite-Cyanates, Kapton, Teflon
- Inflatable Antenna Experiment
- Conductive coatings & threads in development; some long-term coatings/films
- Electric motors, piezoelectrics
- Lubricated hinges/bearings; pyros
- Glass, beryllium, limited Si-C mirrors



SEC Software (Flight & Ground)

What is needed

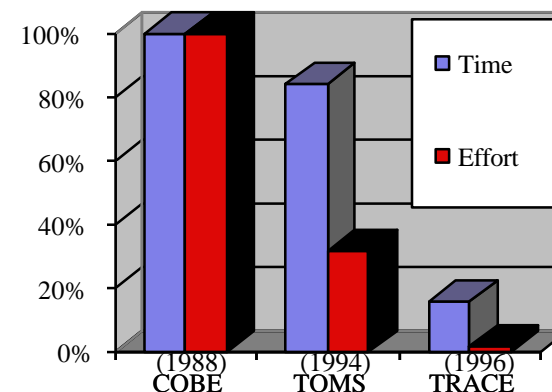
- Low cost, rapid development processes for highly reliable, integrated flight/ground software
 - Software reuse/COTS integration
 - Information Systems standards
 - Automation of Software generation
- High performance simulation & modeling
- Advancements in specific S/W areas supporting science analysis and data management

Goal & Benefit

- Reduced cost and schedule
 - Leveraged S/W development
 - Easier system integration and evolution
 - Reduced S/W V&V costs
- Integrated modeling and observation & real-time spacecraft simulation supporting operations
 - Expedited scientific discovery and efficient use of data from many widely separated spacecraft.

Today's State-of-the-Art

- Emerging efforts in domain specific software applications supporting reuse, automation & standardization.
- Off line modeling: Supports planning & analysis, but not operations
- Multiple analysis efforts. More focus needed on specific SEC missions. Distributed data management activities almost exclusively ground based.



Technology Impacts on Reference Missions

| | Technology Areas | | | | | | | | |
|--------------------|------------------|----------|----------|----------|----------|----------|----------|-----------|----------|
| | Arch & | Oper & | Advan | Power | Rad Hrd | GN&C | Design | Mat'ls | Software |
| Mission name | Interface | Comm | Pack'g | Systems | Data Sys | | Envir | Structure | |
| Solar Probe | ++ | ++ | ++ | ++ | ++ | + | ++ | ++ | ++ |
| Constellation | | ++ | ++ | + | ++ | | ++ | + | ++ |
| IIM | + | + | + | + | + | + | + | + | + |
| Int. Probe (SGA) | ++ | ++ | ++ | ++ | ++ | ++ | ++ | ++ | ++ |
| Solar Stereo | + | ++ | + | | + | + | | | + |
| Jup. Pol Orbiter | ++ | ++ | ++ | ++ | ++ | ++ | ++ | ++ | ++ |
| Solar Sentinel | ++ | ++ | ++ | + | + | ++ | ++ | ++ | + |
| HESP | | + | + | | + | + | ++ | + | + |
| Solar-B | | | | | | | | | + |
| Mag. Tour | + | ++ | + | + | ++ | + | ++ | ++ | ++ |
| Merc. Orbiter | + | + | ++ | + | + | + | + | ++ | ++ |
| Mesosp. Coupler | + | + | + | + | + | + | + | + | + |
| Stereo Magneto. | + | + | + | + | + | + | + | + | ++ |
| Glob.Elec.Dyn. | + | + | + | + | + | + | + | + | + |
| Mars IIM | + | ++ | + | | | | | + | ++ |
| Total ++ | 4 | 8 | 6 | 3 | 5 | 3 | 7 | 6 | 8 |
| Total + | 8 | 6 | 8 | 8 | 8 | 9 | 5 | 7 | 7 |
| Total blank | 3 | 1 | 1 | 4 | 2 | 3 | 3 | 2 | 0 |
| Rank | 3 | 1 | 2 | 3 | 2 | 3 | 1 | 2 | 1 |

KEY: ++ Technologies which provide a very strong technical or programmatic advantage

 + Technologies which provide a significant technical or programmatic advantage

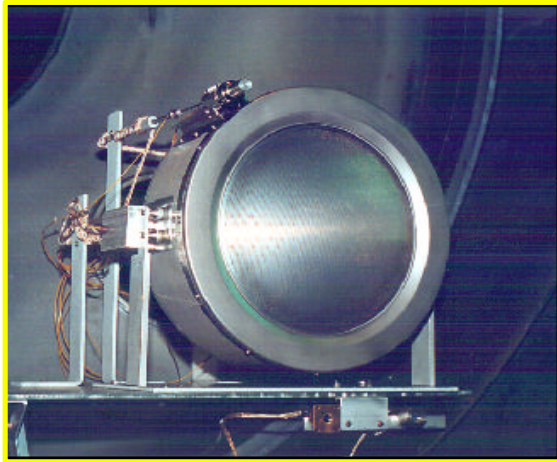
 blank No significant advantage

Matrix identifies high leverage investment areas

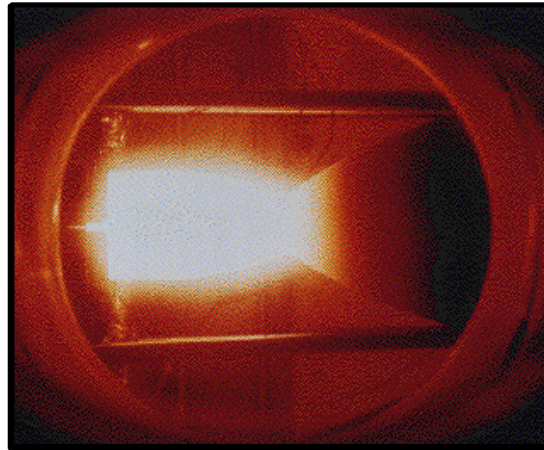
Overall rank is more important than any one line

Spacecraft Systems Conclusions

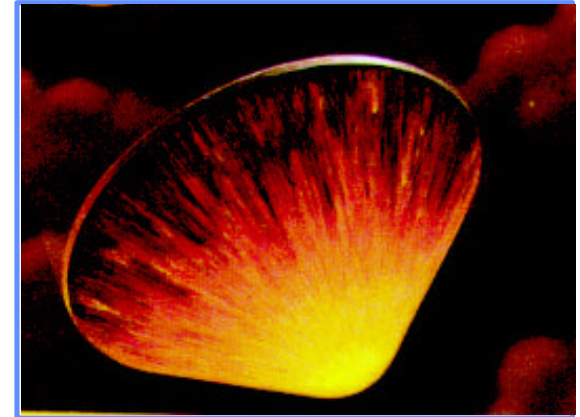
- Greatest general impact on reference mission set in cost reduction areas
 - Operability & Communications
 - Design Environments
 - Software
- Miniaturization and ruggedness characterize next tier of priorities
- Other areas important (and even enabling for specific missions)



Electric Propulsion



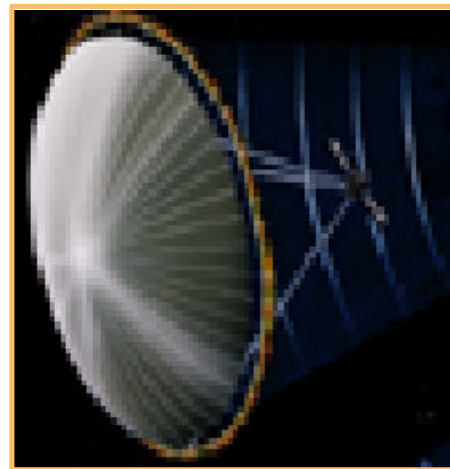
Advanced Chemical
***Transportation
&
Mobility***



Aero Gravity Assist



Tethers



Solar Sails



Low Cost Boost
and Orbit Transfer

Primary Electric Power (SEP)

What is Needed

- Long Life, High Isp Electrostatic systems
 - NSTAR
 - Low Alpha NSTAR derivatives
 - High Total Impulse
 - Low Power
 - “Direct Drive” Systems

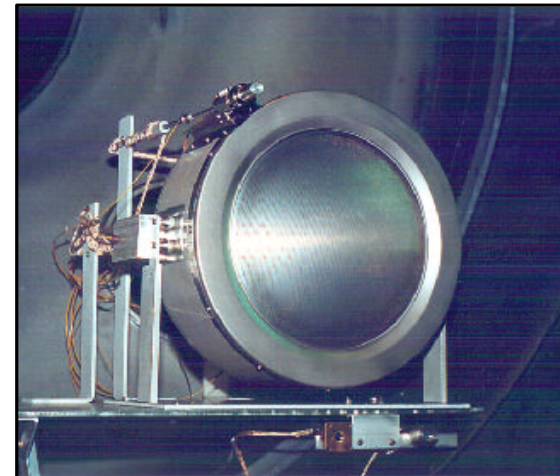
Goal and Benefit

- Requirement
 - 2x to 4x increase in total impulse
 - 3x to 5x decrease in specific mass (incl. power)
- Purpose
 - Reduced Launch Vehicle requirements and/or increase payload mass
- Mission Classes
 - Solar Probe, Stereo, Mercury Orbiter, Jupiter Polar Orbiter, Magnetospheric Constellation

Near Term State-of-the-Art

- NASA’s Solar Electric Propulsion Technology Applications Readiness (NSTAR) System
- Total Impulse: 2.5×10^6 N-sec
- Power: 0.5 to 2.6 kW
- Isp: ~3000 sec
- System Mass: 44 kg

Near Term State-of-the-Art



Auxiliary Electric Power (SEP)

What is Needed

- Miniature Electric Thrusters for
 - Small Satellites insertion, control, deorbit
 - Formation flying
 - Solar Sails

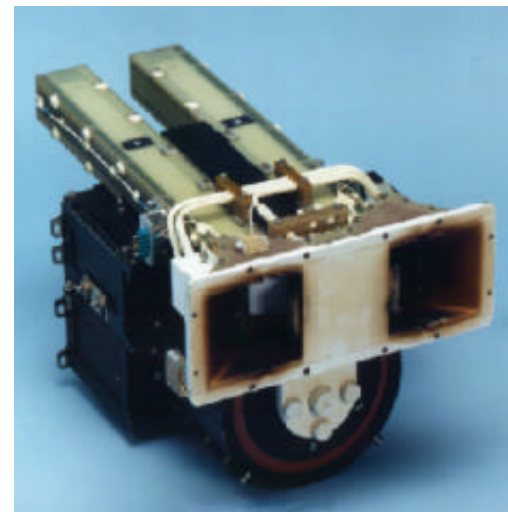
Goal and Benefit

- Requirement
 - 10X reduction in System Mass
 - 5X increase in Total Impulse
- Purpose
 - ACS for spacecraft, autonomous control
 - Primary and Secondary Propulsion for miniature spacecraft
- Mission Classes
 - HESP, STEREO, Solar Probe

Today's State-of-the-Art

- 1980's Vintage LES 8/9 & TIP/NOVA Pulsed Plasma Systems
 - Total Impulse: 6000 N-sec
 - System Mass: 7kg

Today's State-of-the-Art



Advanced Chemical

What is Needed

- High Isp Bipropellants for Insertions/Capture
- High Isp-Density, Non-Hazardous Monoprop for Midcourse Corrections, Primary ²V

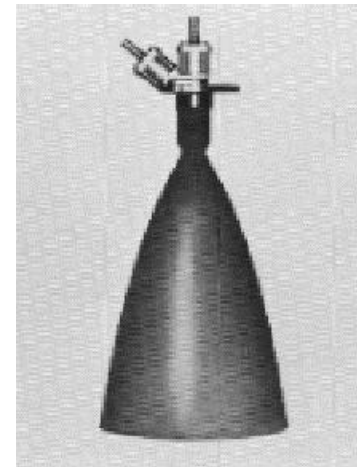
Goal and Benefit

- Requirement
 - Low cost, “Green” Monopropellant system
 - 330 -350 sec Isp Miniature Biprop
 - Microsystems
- Purpose
 - Propellant Mass and Volume savings for Primary ²V and Planetary capture
- Mission Classes
 - HESP, Solar Probe, Magnetospheric Tour, STEREO, Mars Upper Atmosphere Explorer, Jupiter Polar Orbiter, STEREO Magnetospheric Dynamics, Magnetospheric Constellation, ITM Dynamics, Global Electrodynamics, Mesosphere Coupling

Today’s State-of-the-Art

- Hydrazine Monopropellant Systems
 - Toxic, Isp~225 sec
 - Silicide-coated niobium Biprops
 - 309 sec Isp NTO/MMH
 - 314 sec Isp NTO/N₂H₄

Today’s State-of-the-Art



Solar Sails

What is Needed

- Propulsion that is
- Very Low Cost
- Low Launch Volume
- Long Life (no expendables)
- No Contamination
- Low Mass

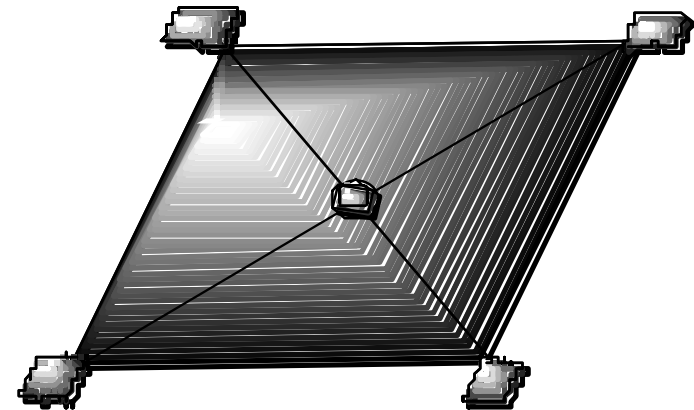
Goal and Benefit

- Technology Goals
 - $(50 \text{ m})^2$ to $(300 \text{ m})^2$ Size Solar Sails
 - Lightweight Inflatable Structures $<15 \text{ g/m}^2$
 - Lightweight Mechanical Structures
- Purpose
 - High ΔV , Low Cost, Low Mass, Low Volume, Long Life, No Contamination
- Mission Classes
 - Solar Probe, Solar Polar, Solar Stereo, Solar Sentinel, Mercury Orbiter

Today's State-of-the-Art (100 m x 100 m Sail)

- Thin Film Sail 150kg
 - $7.6 \mu\text{m}$; 1.4 g/cm^3
- Aluminum Coating 1 kg
- Deployment/Structure 45 kg

Today's State-of-the-Art



Long Life Tethers For Multipoint Measurements & Formation Flying

What is Needed

- Precision formation flying for in-situ atmospheric and ionospheric measurements using multiple spacecraft joined by kilometers-long tethers
- Low-drag (to minimize propellant)
- Micrometeoroid and debris survivability (>99% over 1 year desired)

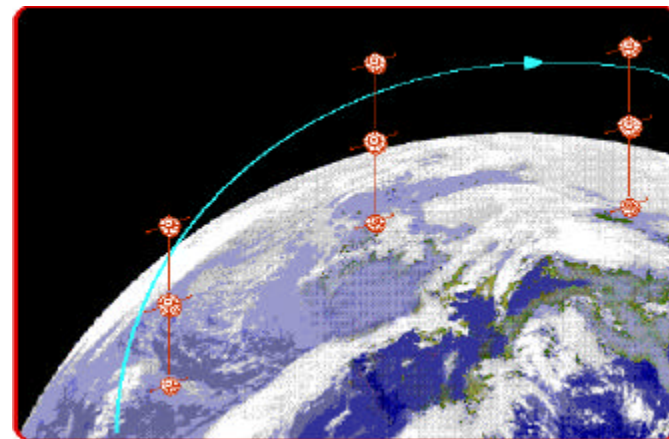
Goal and Benefit

- Requirement
 - Long-Lived, Highly-Survivable, Light-Weight Tether(s)
- Purpose
 - Enables multi-point, precision in-situ measurements of the ionosphere
- Mission Classes
 - Mars Upper Atmosphere, Magnetosphere Constellation, ITM Dynamics, Global Electrodynamics

Today's State-of-the-Art

- 16 Tether Missions Flown Since 1966
 - Micrometeoroid and debris survivability attained through use of thick tethers (incl. TiPS, now on-orbit); high drag approach
- Multiline 'Hoytethers' being developed to provide low-drag alternative for survivable tethers.

Conceptual Formation



Electrodynamic Tether Propulsion

What is Needed

- Light-weight propellantless propulsion system for extended Jovian or LEO science missions
 - Altitude and inclination changes possible
- Micrometeoroid and debris survivability (>99% over 1 year desired)

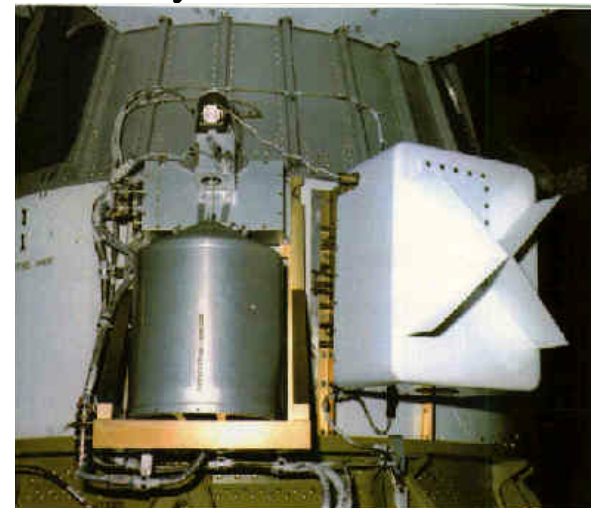
Goal and Benefit

- Requirement
 - Propellantless propulsion for long-duration Jovian exploration
- Purpose
 - Enables extended Jovian exploration with reduced spacecraft propellant requirements
- Mission Classes
 - Jupiter Polar orbiter

Today's State-of-the-Art

- Plasma Motor Generator experiment demonstrated electrodynamic tether propulsion and power generation
 - Delta II secondary payload
- Reflight of Tethered Satellite System demonstrated electrodynamic tether drag thrust of 0.4 N
- Proposed mission will demonstrate thrust using a small deployer (2000 flight planned)

Today's State-of-the-Art



TSS-1R

Aeroassist* for Jupiter / Mars Missions

What is Needed

- Atmospheric Constituents
- Atmospheric Models
- Navigation / Guidance Aids
 - Beacons / satellites
- Guidance , navigation, and control algorithms
- TPS Materials
- Structures

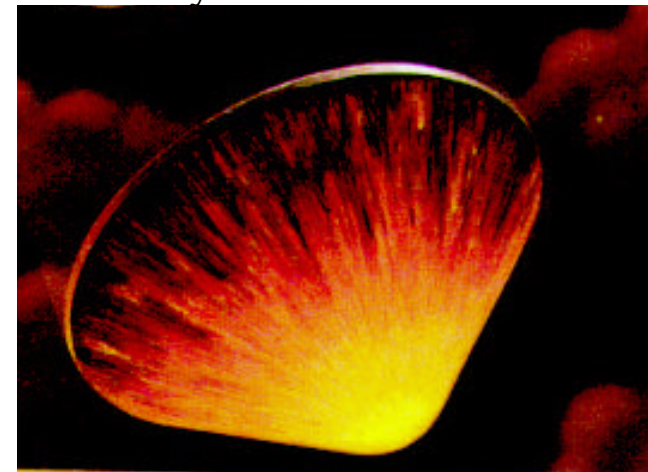
Goal and Benefit

- Requirement
 - Use planetary atmosphere to aerocapture spacecraft into orbit
- Purpose
 - Enables significant mass savings due to reduced propellant savings
- Mission Classes
 - Mars Upper Atmosphere, Jupiter Polar Orbiter

Today's State-of-the-Art

- Mars Global Survey spacecraft
 - In 1997 will use aerobraking to lower highly elliptical orbit to operating altitude
 - Mars Global Survey spacecraft
- Before cancellation in 1987, spent \$ 100M in on Aeroassist Flight Experiment (AFE) to demonstrate earth capture from geosynchronous orbit

Today's State-of-the-Art



*Includes aerogravity assist, aerocapture, and aerobraking 35

Sun-Earth Connection (SEC) Missions and Technologies

| Missions>> Technology | HESP | Solar-B | Solar Probe | Inter-stellar Probe | Magneto-spheric Tour | Stereo | Mercury Orbiter | Mars Upper Atmosphere | Jupiter Polar Orbiter | Stereo Magneto-spheric Imager | ITM Constellation | ITM Dynamics | Global Electro-dynamics | Solar Wind Sentinel | Meso-sphere Coupler |
|-------------------------------|------|---------|-------------|---------------------|----------------------|--------|-----------------|-----------------------|-----------------------|-------------------------------|-------------------|--------------|-------------------------|---------------------|---------------------|
| Solar Sail | | | X | | | X | X | | | | | | | X | |
| Primary Electric Propulsion | | | X | X | | X | X | | X | | X | | | | |
| Electro-dynamic Tethers | | | | | | | | | X | | | | | | |
| Tethers | | | | | | | | X | | | X | X | X | | |
| Auxiliary Electric propulsion | X | | | | | X | | | | | | | | | |
| Advanced Chemical | X | | X | | X | X | | X | X | X | X | X | X | | X |
| Aerocapture | | | | | | | | X | X | | | | | | |

X - Advanced Transportation Technology Enables or Significantly Enhances Mission Concept

SEC Transportation and Mobility Recommendations

Specific Technology Recommendations

- Electric propulsion technology program impacts a broad class of SEC missions.
 - »Primary electric is near-term enabling for many SEC missions
 - »Auxiliary electric is enhancing and high-leverage with other programs
- Advanced chemical propulsion development important for all SEC mission classes.
 - »Need micropropulsion technology program for miniature spacecraft
- Aeroassist program needs to be expanded to address requirements of SEC planetary missions.
- Feasibility of solar sails needs to be determined for solar and interplanetary SEC mission classes.
 - »Coordinate with NASA Advanced Space Transportation Program
- Multipoint tether development needs to be expanded for in-situ planetary ionospheric and magnetospheric SEC mission classes.
 - »Demonstrate long-life and multipoint technologies
- Electrodynamic tether propulsion program needs to be augmented to determine feasibility for Jupiter Polar Orbiter Mission
 - »Coordinate with NASA Advanced Space Transportation Program
- Maximize leverage through coordination with NASA Advanced Space Transportation Program and other national programs

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